

An ET Origin for Stratospheric Particles Collected During the 1998 Leonids Meteor Shower

David A. Noever*, James A. Phillips[†], John M. Horack*,
Gregory Jerman*, and Ed Myszka[‡]

*Science Directorate, NASA/Marshall Space Flight Center, Huntsville, AL 35812
david.noever@msfc.nasa.gov
john.horack@msfc.nasa.gov
gregory.jerman@msfc.nasa.gov
256 544 1872
256 544 5800 (fax)

[†]BishopWebWorks, 162 Alpine Drive, Bishop, CA, 93514
phillips@spacesciences.com
760 873 5585
760 872 1382 (fax)

[‡]CSC Corporation, SD-01, NASA/Marshall, Huntsville, AL, 35812
ed.myszka@msfc.nasa.gov
256 544 1032
256 544 5800

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Abstract

On 17 November 1998, a helium-filled weather balloon was launched into the stratosphere, equipped with a xerogel microparticle collector. The three-hour flight was designed to sample the dust environment in the stratosphere during the Leonid meteor shower, and possibly to capture Leonid meteoroids. Environmental Scanning Electron Microscope analyses of the returned collectors revealed the capture of a $\sim 30\text{-}\mu\text{m}$ particle, with a smooth, multigranular shape, and partially melted, translucent rims; similar to known Antarctic micrometeorites. Energy-dispersive X-ray Mass Spectroscopy shows enriched concentrations of the non-volatile elements, Mg, Al, and Fe. The particle possesses a high magnesium to iron ratio of 2.96, similar to that observed in 1998 Leonids meteors (Borovicka, *et al.* 1999) and sharply higher than the ratio expected for typical material from the earth's crust. A statistical nearest-neighbor analysis of the abundance ratios Mg/Si, Al/Si, and Fe/Si demonstrates that the particle is most similar in composition to cosmic spherules captured during airplane flights through the stratosphere. The mineralogical class is consistent with a stony (S) type of silicates, olivine $[(\text{Mg,Fe})_2\text{SiO}_4]$ and pyroxene $[(\text{Mg,Fe})\text{SiO}_3]$ —or oxides, hercynite $[(\text{Fe, Mg})\text{Al}_2\text{O}_4]$. Attribution to the debris stream of the Leonids' parent body, comet Tempel-Tuttle, would make it the first such material from beyond the orbit of Uranus positively identified on Earth.

Proposed Running Head: *ET Origin for Particles Captured During the 1998 Leonids*

Leonid meteoroids contribute a significant fraction of the annual budget of cosmic material falling on Earth (Rietmeijer 1999), and numerous groups (e.g., Blanchard *et al.* 1969, Maag *et al.* 1993) have attempted to capture and retrieve them for analysis. There have also been unintended captures of Leonid particles by low Earth orbit (LEO) satellites (Humes and Kinard 1997). In 1969, 32 partially melted meteoroids were collected (Brownlee and Hodge 1969, Brownlee *et al.* 1997) by flying U2 and WB57 aircraft at stratospheric altitudes near 20 km. These meteoroids were members of a general low-level flux of particles that produce an average zenithal hourly rate (ZHR) of visual meteors near 6/hr on a daily basis. This work has led to a better understanding of meteoroid compositions and ablation mechanisms. However, there has since been no systematic effort to sample and study extraterrestrial particles in the stratosphere in general, or the Leonids in particular. The upper stratosphere remains perhaps the best environment to collect meteor dust, however success in doing so is a compromise between environmental and technical factors (Rietmeijer 1999).

On 17 November 1998 we launched a 10m weather balloon equipped with an xerogel dust collector to sample the stratosphere during the peak flux of the Leonids. A matrix of low-density silica xerogels in separated polystyrene wells were fixed to the outside of the balloon package. The payload was carried to an altitude above 98% of Earth's atmosphere during a 1.9 hr flight. An on board digital camera captured eight Leonid fireballs brighter than magnitude -10. At its maximum altitude, the balloon ruptured as planned and the payload descended to Earth by parachute. Eight candidate impactors were analyzed in the returned payload. One of these exhibits chemical and morphological signatures indicating extraterrestrial origin.

Twenty-four one-inch-diameter circular wells of xerogel were sent aloft to the stratosphere and only a few were damaged during the balloon's descent and landing. A visual microscopic survey of the remaining xerogel containers revealed that all were pitted with

craters in the 20 - 100 micron range (e.g., Figure 1). Based on the apparent density of craters in each capture well, we selected one 1-inch diameter circular sample for further study with an Environmental Scanning Electron Microscope (ESEM) (Danilatos *et al.* 1982). The ESEM, which does not require hard vacuum conditions to reduce scattering, is normally used to study wet, biological samples. Its advantage for the Leonids sample return is that it is unlikely to cause vacuum damage to fragile microparticles. The ESEM was equipped with a 20 keV energy dispersive X-ray mass spectrometer (EDS) sensitive to elements with atomic weights $Z > 10$. Using the SEM and EDS together, we can image each impactor while simultaneously characterizing its elemental composition.

We scanned the xerogel sample to a surface depth of 1-2 micron using a rastered beam similar in size to the diameter of the impactors (10 - 10,000x, sample-dependent 4 nm resolution). These instrument settings were selected to avoid sources of error involving resolution and diffraction effects. ESEM-EDS analysis of the xerogel capture media revealed a smooth silica surface to the resolution of approximately 1 micron and chemical analysis showed Si:O ratios between 2:1 and 3:1, as expected. Residual levels of Fe, Mg, Ni, Ca, Al and C were below 1% detection thresholds.

The eight crater-like pits were examined in the same fashion as the xerogel background. Each crater contained a single impactor ranging in size from 1 - 40 microns. These particles fell into two categories differentiated by morphology and chemical composition.

Seven particles were similar; spherical in shape (Figure 2a) with a strong signature of Si. The dominance of Si in the spectra of these particles makes accurate abundance measurements difficult because of possible confusion with the Si-rich xerogel capture media. The shape of the particles suggests that they have experienced sufficient heating – possibly a result of atmospheric friction – to render them molten before cooling and reforming as a sphere. Without more reliable abundance measurements it is impossible to say whether or not these seven impactors have an extraterrestrial origin.

An eighth candidate stood out as distinct from the others. EDS data (Figure 2b) showed that this impactor is rich in Si, but also has significant concentrations of Mg, Al, and Fe. The particle is irregular in shape with translucent rims and an opaque core, much like known cosmic spherules (Brownlee *et al.* 1997). There is no sign of bulk melting. The general morphology of this 30 μm particle is also similar to that of Antarctic micrometeorites composed of silicates in the 50 - 100 μm range (Genge *et al.* 1996).

No degassing vesicles or gas corrosion from volatiles are apparent as might be expected for intensely heated particles. It is nevertheless rich in the non-volatile elements Mg, Al, Si and Fe (see Fig 2C). Abundance ratios of Mg, Al, Si and to a lesser extent Fe have previously served (Brownlee and Hodge 1969, Love and Brownlee 1991, Love and Keil 1995) for identification of cosmic particles in three broad categories: a dominant type S (stony), and less frequent types I (iron) and FSN (iron-nickel-sulfur). S-types, which are thought to arise from asteroids, dominate the background terrestrial flux. In stratospheric collections of microparticles, FSN types feature prominently but rarely exceed 20 μm in diameter. The strong Si peak in all the EDS analyses (Figures 2a,b) excludes this particle from the I-spherules which contain no silicates.

The ratios Al/Si, Mg/Si and Fe/Si obtained for the irregular Leonid meteoroid candidate appear in the first three data columns of Table 1 along with average ratios for known cosmic spherules, meteorites, and typical terrestrial dust. Also tabulated are the ratios for an xerogel control sample which remained on Earth during the balloon flight. The composition of the Leonid candidate is clearly similar to that of cosmic spherules previously found on Earth, and much less like that of Earth dust or the control.

A special subclass of vitreous S-type cosmic spherules have previously been detected and identified in stratospheric collections (Brownlee and Hodge 1969, Brownlee *et al.* 1997). Members of the subclass smaller than $\sim 30 \mu\text{m}$ were enriched in Al and depleted in Fe relative to parent chondritic material. This Leonid candidate may be related to these

particles, as it is also rich in aluminum (Al/Si=0.56), and slightly depleted in magnesium (Mg/Si=0.89) and iron (Fe/Si=0.30) compared to median cosmic spherules from deep sea, Antartic, and stratospheric collections (Brownlee *et al.* 1997).

Also notable is the Leonid candidate’s high magnesium to iron ratio. Airborne UV/Vis spectroscopy of a bright 1998 Leonids meteors show atomic metal spectral lines indicating Mg/Fe \approx 3.3 (Borovicka *et al.* 1999). This is in good agreement with the high Mg/Fe ratio of the Leonid sample (2.96) and in sharp contrast to the low ratio expected for typical material from the earth’s crust (Mg/Fe \sim 0.4).

Iron/Nickel ratios can effectively discriminate between terrestrial and extraterrestrial origin of stratospheric dust (Rietmeijer 1999). Terrestrial dust particles tend to have high ratios. For example, volcanic ash from Mt. St. Helens collected at 34-36 km altitude had Fe/Ni=1200. Extraterrestrial dust exhibits much lower ratios, e.g., optical spectra of meteors yield Fe/Ni \sim 19. Nickel was not detected in the EDS spectrum of the Leonids candidate, as the Ni peak was below the 3σ noise level of 1% fractional composition. The Fe peak was measured at 9%, placing a lower limit of Fe/Ni $>$ 9. This test does not yield discrimination between terrestrial and extraterrestrial dust.

To test the extraterrestrial hypothesis further, we use a statistical procedure to compare EDS data with the chemical makeup of cosmic microparticles in various sampling databases (Rietmeijer 1999, Brownlee *et al.* 1997). We express compositional ratios as a vector X with components (Mg/Si, Al/Si, Fe/Si). The ‘chemical distance’ R_{Lj} between the Leonid candidate (L) and any other material (X_j) may then be evaluated as

$$R_{Lj} = \sqrt{\sum_{i=1}^3 (L_i - X_{ij})^2}. \quad (1)$$

This formulation allows us to compare and classify objectively the Leonid candidate with nearest neighbors based on their minimum Euclidian distance. These data are contained in the fourth column of Table 1, and the “chemical distance” vectors are plotted in Figure 3.

These data clearly indicate that the 1998 Leonid candidate is closest in composition to coarse unmelted cosmic spherules captured during previous airplane flights through the stratosphere. The low concentration of iron in those spherules, relative to the Leonid candidate, may result from volatilization of iron sulfide during atmospheric entry or perhaps unique chemical features for Leonids-related dust streams. While the composition of the Leonid candidate does not perfectly match that of any catalogued cosmic spherule, the chemical distance is relatively small. Importantly, the Leonid particle is significantly more distant from the control than the cosmic particles, and lies *most* distant from terrestrial dust.

This analysis shows conclusively that the Leonid candidate is most chemically similar to known extraterrestrial particles. Both its composition and morphology are consistent with that of micrometeoroids previously gathered from the stratosphere and elsewhere. Taken together, we believe the chemical and morphological properties are most consistent with the explanation of an extraterrestrial origin.

However, there are factors which may contravene these conclusions. It is difficult to estimate *a priori* capture probabilities relevant to this experiment, as little is known about the stratospheric particle environment during an intense meteor shower. For satellite impacts during the 1998 shower, a flux of $0.4\text{--}59\text{ m}^{-2}\text{ hr}^{-1}$ was predicted,⁷ corresponding to an expected maximum of ~ 2 impacts/hr for the $\sim 600\text{ cm}^2\text{ hr}$ area-time product for this flight. While comparable to that observed, the figure is unlikely to be meaningful in this context. The ‘true’ expected value at 20 km depends on a very uncertain extrapolation of meteoroid momenta and densities from the top of Earth’s atmosphere downward to the stratosphere.

The xerogel dust collector was exposed for the entire duration of the balloon flight from launch to landing. We cannot exclude the possibility that metal-rich contaminants such as volcanic dust or industrial pollutants were captured at low altitudes. Small ($<$

10-15 μm) volcanic ash particles have been captured in the upper stratosphere (Rietmeijer 1993, Testa *et al.* 1990), and some terrestrial particles, albeit atypical ones, are found to have high Al content as does the Leonids candidate. Future balloon flights, including one scheduled for the 1999 Leonids meteor shower, will carry a remotely controllable sample collector that opens only while the balloon is in the stratosphere.

Meteoroids sampled in the stratosphere enter the atmosphere at high speed, ~ 70 km/s for the Leonids. Terminal velocity for cometary debris in the 20 - 70 micron range is widely thought to be reached at altitudes considerably higher than 20 km, thus requiring a significant ‘drift time’ to reach these lower altitudes. Empirical data has little to say on this point, however, simply because there has been no systematic sampling of stratospheric meteoroid fluxes during major meteor showers prior to 1998. If the Tempel-Tuttle debris stream includes a component of larger-, harder-, and faster-than-average meteoroids, then this balloon would be sensitive to Leonids in real-time during the shower’s peak, rather than older, slower-moving particles.

Even if the particle is extraterrestrial, it is still possible that it did not arise from the debris stream of comet Tempel-Tuttle. Most meteoroids do not plunge directly to Earth after entering the atmosphere. Instead they lose much of their kinetic energy high above the stratosphere and very slowly drift downward. If this scenario applies to the particles captured during the peak of the Leonids meteor shower, they may have entered Earth’s atmosphere days or weeks earlier. The irregular particle might have originated, for example, from the debris stream of comet Giacobini-Zinner which caused an intense meteor shower in October 1998. Alternatively, it could be a member of the low-level background population of meteoroids that permeates the inner solar system. Indeed, the SEM survey of the xerogel collector was a surface scan and, thus, preferentially sensitive to older, lower velocity impactors.

This year our group will execute a systematic campaign of balloon flights during

relatively intense meteor showers and also during periods of low meteor activity to evaluate further the temporal correlation between visual meteor counts and meteoroid flux in the stratosphere. These additional flights may provide the information needed to confirm the present candidate as a Leonid or to assign it to a different meteoroid population.

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TABLE I.

	Mg/Si	Al/Si	Fe/Si		R_{Lj}
1998 Leonids					
Sample	0.89	0.56	0.3		0.000
Control	0.0	0.0	0.0		1.094
Sampling Site					
Stratosphere	1.06	0.233	0.633		0.497
Antarctic	1.06	0.091	0.528		0.549
Deep Sea	1.06	0.083	1.024		0.884
All	1.06	0.094	0.937		0.807
Stratospheric unmelted					
Smooth	0.82	0.082	0.742		0.655
Porous	1.02	0.07	0.705		0.649
Coarse	1.2	0.075	0.585		0.642
Bulk IDP	0.98	0.075	1.08		0.923
Bulk Chondrites					
CI	1.07	0.085	0.9		0.786
CM	1.05	0.095	0.819		0.715
H	0.96	0.07	0.818		0.717
L	0.93	0.069	0.584		0.569
Earth dust*	0.83	< 0.003	2.27		2.048

*values for Earth dust are based on these mass fractional abundances for Earth as a whole: 34.6% Fe, 29.5% O, 15.2% Si, 12.7% Mg, 2.4% Ni, 1.9% S, 0.05% Ti.

TABLE I. Comparison of chemical elemental ratios for non-volatiles in the Leonids candidate particle, along with known cosmic dust, control sample, and terrestrial composition. R_{Lj} expresses the “chemical distance” between the Leonids candidate and other particles as described in the text. The Leonids candidate is most distant from terrestrial composition, and agrees most closely with known cosmic dust.

FIGURE CAPTIONS

FIGURE 1: Sequence showing the cross-section of a particle and impact crater in the xerogel collector. The crater measures 20-30 μ m in diameter.

FIGURE 2a: Representative EDS mass spectrogram and ESEM image of a spherical particle found embedded in the xerogel collector.

FIGURE 2b: EDS mass spectrum of the irregular, non-volatile rich particle with translucent rims and an opaque core, and its ESEM image. The percentage composition of the sample is Si (31%), Mg (28%), Al (18%), O (12%) and Fe (9%) with no appreciable Ni or C.

FIGURE 3: Three dimensional scatter plot of the “Chemical Vectors” (Fe/Si, Al/Si, Mg/Si) for known cosmic particles (square), the leonids ET candidate (filled circle) and for terrestrial dust (triangle). Projections in the XY plane are also shown to aid in visualization. The Leonids sample particle lies most closely to known particles of extraterrestrial origin, and most distant from terrestrial composition.

FIGURES



Figure 1, Noever, et al.; *An ET Origin ...*

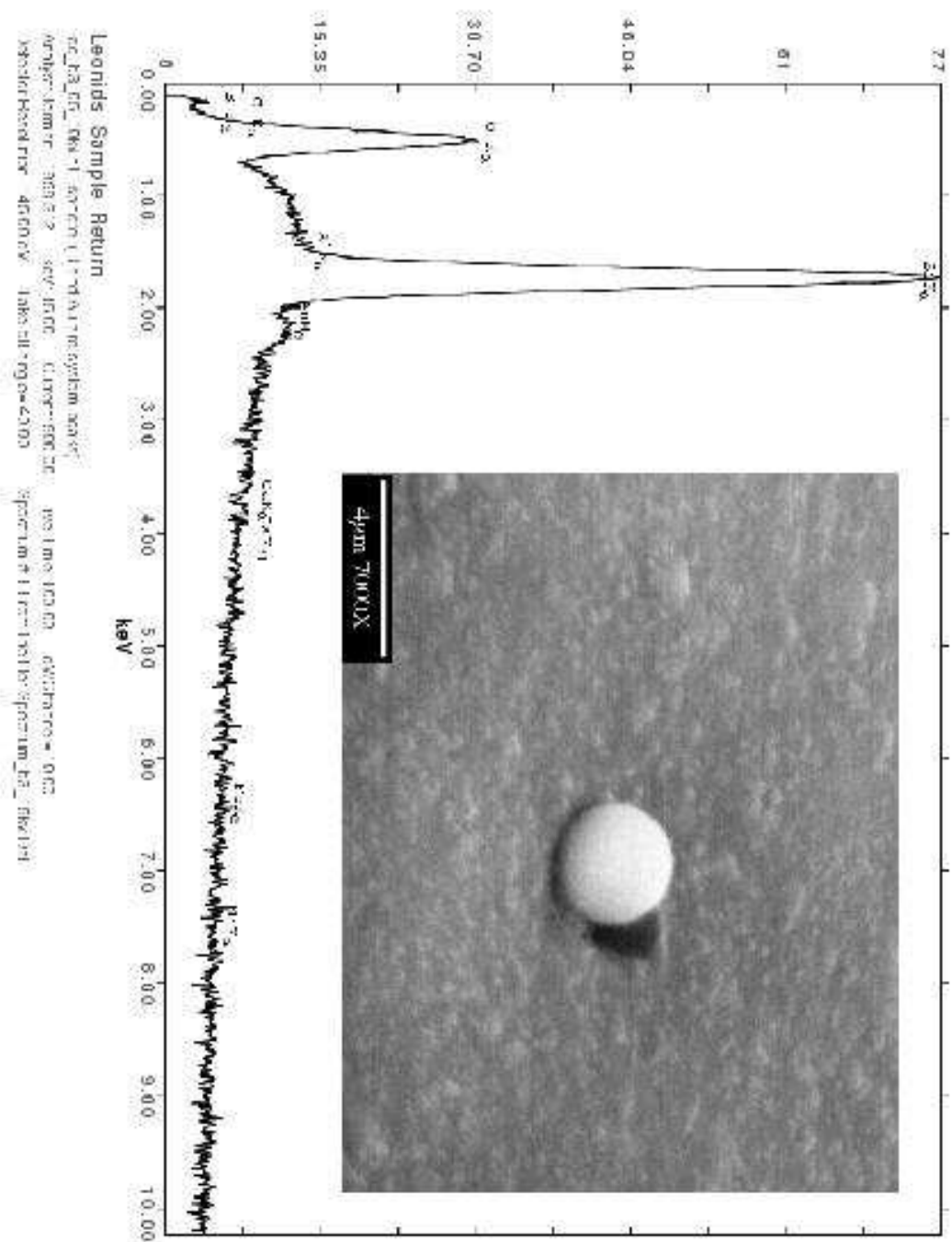


Figure 2a, Noever, et al.; *An ET Origin ...*

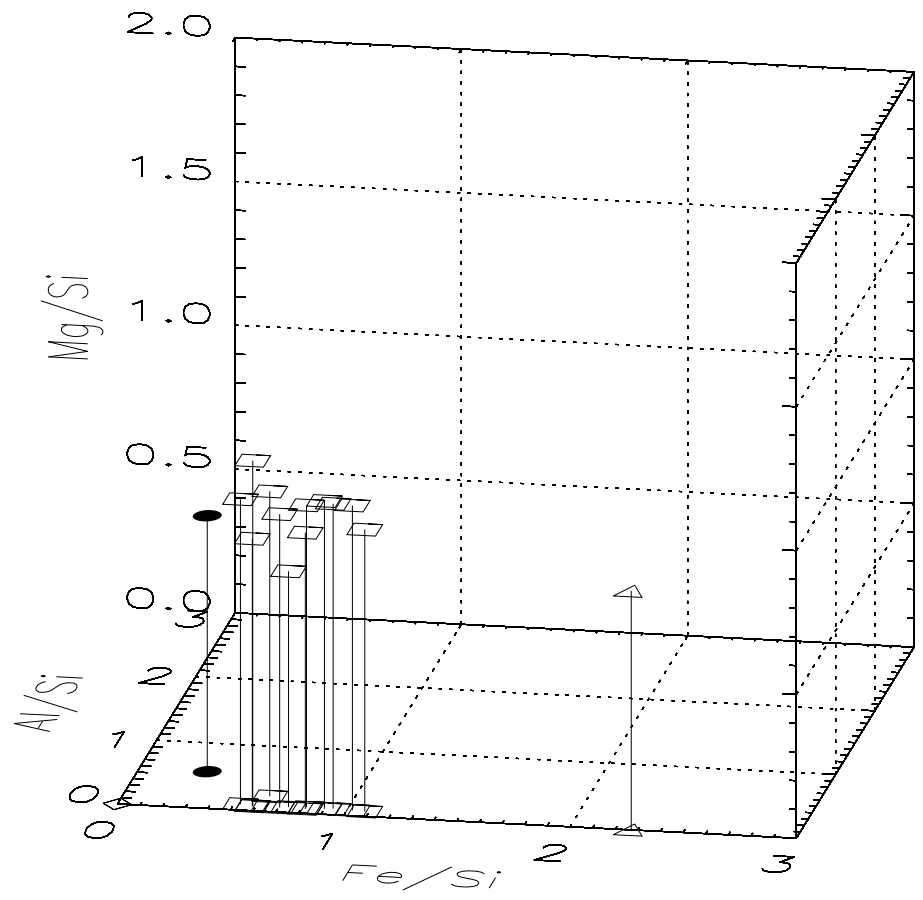


Figure 3, Noever, et al.; *An ET Origin ...*